Explaining annual streamflow variability of Amazonian rivers

ALAN V. LOPES & JOHN A. DRACUP
Civil & Environmental Engineering Department, University of California, Berkeley, Davis Hall 612, California, USA
alanvazlopes@berkeley.edu

Abstract Analysed in this study were the influence of El Niño events and the oscillation of the Intertropical Convergence Zone (ITCZ) on Amazonian rivers. Empirical orthogonal function analysis (EOF) was employed to quantify how much of the annual variability of Amazonian river discharges can be explained by El Niño events and anomalous ITCZ displacement. Normalized time series of the NINO 3.4 index and Atlantic Meridional Mode (AMM) index were analysed together with river discharge measurements at 13 sub-basins and longer reconstructed streamflow time series spanning over 60 years at four sites. The results show that the AMM index explains more of the streamflow annual variability than the NINO 3.4. The annual discharge variability of the rivers that drain from the south area of Amazonia (Xingu and Araguaia), were better explained by NINO3.4 than by AMM. However, a large part of the annual discharge variability of the Amazonian rivers remains to be explained by other phenomena not considered here.

Key words Amazon; streamflow; principal component analysis

INTRODUCTION

El Niño events are associated with negative anomalies of rainfall over the Amazon basin. During El Niño events, anomalous high sea surface temperatures (SST) over the central Pacific Ocean are sustained beyond the normal warm season. The Walker circulation changes are known to reduce and enhance rainfall patterns in many parts of the world (Ropelensky, 1987). In the Amazon basin, rainfall is reduced due to suppressed convection with direct effects on river streamflows. However, El Niño events with different intensities and durations produce different impacts in each sub-basin in Brazil (Lopes & Dracup, 2010).

The intertropical convergence zone (ITCZ) is a region where northern and southern trade winds meet, resulting in deep convection areas with great rainfall intensity. Thus, during the Northern Hemisphere winter, the ITCZ is displaced to the south, increasing rainfall over the Amazon; during the Northern Hemisphere summer, the ITCZ is displaced to the north, reducing rainfall over the Amazon. Some studies suggest that ITCZ displacements are related to the SST gradient across the Atlantic Ocean (Nobre, 1996). Therefore, in this study, the Atlantic Meridional Mode (AMM), a climatic index related to the SST gradient across the Atlantic Ocean, is used as an indicator of anomalous ITCZ displacements (Chiang *et al.*, 2002).

Besides SST over the Pacific and Atlantic oceans, several other factors may influence annual streamflow variability in Amazonian rivers, including other low-frequency climatic phenomena such as the Pacific Decadal Mode, the river basin hydrological characteristics and even randomness. Principal component analysis (PCA) can be used to identify the different modes of annual variability of streamflow. Then the influence of climatic phenomena over these modes can be evaluated by correlation. In this paper, streamflow time series for 13 sub-basins of the Amazon River basin were used to extract the principal modes of annual variability. Also, reconstructed longer streamflow time series were used to derive principal components (PCs) spanning longer periods. Those PCs were then correlated to SST indexes over the Pacific and Atlantic oceans in order to evaluate their influence on annual streamflow variability.

DATA AND METHODS

Streamflow time series (1928 to 2010) for the Amazon rivers used in this analysis were obtained from the Brazilian National Water Agency (ANA, http://hidroweb.ana.gov.br). For the period from 1968 onward the time series consisted of field discharge measurements. However, for some of the locations the time series were reconstructed in the following way. For the Madeira River, the streamflow time series at Porto Velho was reconstructed using measurements of water level from 1908 to 1946 and multiple regression with rainfall data from 1947 to 1968. For the Amazon River at Obidos the time series from 1928 to 1998 consist entirely of field measurements however; data from the period 1949 to 1967 are missing and were not included in the analysis. For the Teles Pires and Xingu (at Belo Monte) rivers the time series from 1931 to 1968 was obtained by rainfall–runoff modelling. All streamflow annual average time series were normalized by the long-term mean and when the data were not available the year was excluded from the time series, forming composites which were then used for the derivation of PCs. It is worth noting that all streamflow time series are natural as they have not been impacted by hydropower dams or other human activities.

El Niño events were analysed using the NINO 3.4 index, which is the monthly SST averaged over the region confined by the meridians 120W and 170W and by the parallels 5N and 5S. That index is provided by the National Oceanic and Atmospheric Administration (NOAA, http://www.cpc.ncep.noaa.gov/data/indices) and covers the period 1950–2010. The SST monthly values were used to derive annual average values for the period from June to May previous to the hydrological year in each sub-basin. Then the annual time series was normalized by the long-term mean. The average in the period from June to May was correlated to annual streamflow for the year ahead since a delay in hydrological response to El Niño was identified (Lopes & Dracup, 2010).

The SST index AMM over the Atlantic Ocean was used as a surrogate indicator for ITCZ displacements, given the association of ITCZ movements with SST gradients across the Atlantic Ocean. Monthly values of AMM from NOAA were used to derive annual time series covering the period from 1950 to 2010.

Principal component analysis is used to transform a set of time series or vectors with some correlation with each other into another set of time series or vectors that are orthogonal and therefore have no correlation to each other. The transformation is achieved by deriving the eigenvalues and eigenvectors of the covariance matrix of the original set of vectors. When the values of each vector have different orders of magnitude (as in the case of streamflow records in different river basins), it is recommended that the covariance matrix be derived from normalized vectors (Wilks, 1995). The total variances of both sets of vectors are equal and the variances in the transformed set of vectors can be added up since they are orthogonal to each other. The transformed set of vectors can then be ordered by the value of their variance in order to identify those vectors that sum the greater amount of variance. Usually a very small number of vectors (or components) carry the major part of the total variance.

Following the conventional procedure outlined above, the PCs were derived for each of the seven sets of streamflow time series as described in Table 1. The sets of streamflow time series are identified by the letters A, B, C, D, E, F and G in Table 1 and are composed of data from different sites, with different common periods of available data. The derivation of PCs for different sets of time series was determined to evaluate which sites should be included or excluded from the derivation of PCs. For example, if the time series set A results in the same PCs as derived from the time series set G, then we can conclude that the three sites of the time series set G are sufficient to derive PCs as they will be similar to the PCs of the time series set A. Therefore, 10 of the 13 sites in the time series set A could be excluded without much loss of information in the PCs. Moreover, a longer period could be covered by the PCs derived from time series set G as it has a longer common period of available data among the three sites. Naturally, PCs covering longer periods are preferred for the further analysis of correlation with external forcing mechanisms, such as SST.

Very few sites have long streamflow time series; however, those sites are associated with large drainage areas that cover a significant part of the Amazon River basin. Only the time series sets F and G include time series covering the longer periods from 1932 to 2007, as shown in Table 1. However, only parts of these time series were used in the correlations with climatic indexes, such as NINO 3.4 and AMM, as their time series begin in 1948.

Table 1 Time series sets used to derive principal components.

Time series set	Sites used	Period covered
A	All 13 sites: Gaviao, Sao Francisco, Porto Gauchos, Fontanillas, Prainha, Serrinha, Santo Antonio Ico, Seringal Labrea, Porto Velho, Manacapuru, Obidos, Belo Monte	1979 to 1997 (1991 and 1996 missing)
B	10 sites: all but Fontanilla, Seringal, Obidos	1978 to 2007 (1997 and 2002 missing)
C	8 sites: all but Fontanilla, Seringal, Obidos, Prainha, Serrinha	1974 to 2007 (1997 and 2002 missing)
D	5 sites: Seringal, Labrea, Porto Velho, Belo Monte, Obidos	1971 to 1997
E	4 sites: Seringal, Labrea, Porto Velho, Belo Monte	1968 to 2006
F	4 sites: Porto Velho, Teles Pires, Belo Monte, Obidos	1932 to 1997 (1947 to 1970 missing)
G	3 sites: Porto Velho, Teles Pires, Belo Monte	1932 to 2007

Finally, the indexes NINO 3.4 and AMM were correlated to the first three PCs from the sets of time series in order to evaluate how much each SST index explains the principal modes of annual variability. Each PC from each time series set was individually analysed with each index to find the strongest correlation.

RESULTS

The sum of the variances of the first three PCs derived from the time series set A (Table 1) corresponds to 77% of the total variance of that set. Thus, the time series at the 13 different sites were strongly correlated to each other and therefore it is very likely that the same physical mechanisms drive the annual variability in all 13 sites. Moreover, those physical mechanisms can be investigated by looking at the first three PCs as they explain most of time series annual variability.

The first PC derived from the time series sets A, B and C are strongly correlated to each other, as shown in Fig. 1 (the correlations between A and B is 0.99, between A and C is 0.97 and between B and C is 0.98). Thus, the first PC derived from the time series set C (with only 8 sites) is about the same as those derived from time series sets A and B (with 13 and 10 sites) and covers a longer common period of available data. A similar result is obtained for the first PCs derived

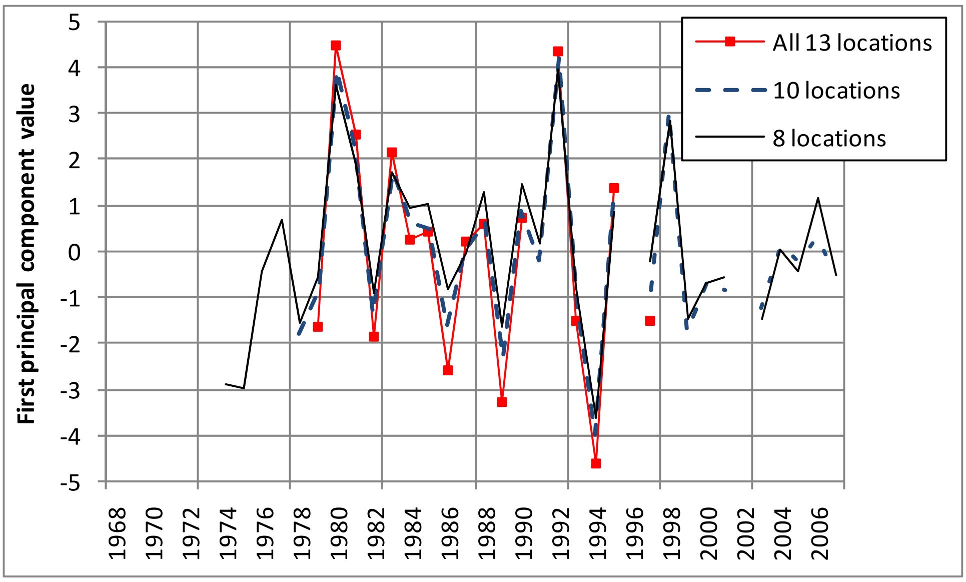

Fig. 1 First principal components from the time series sets A, B and C in Table 1.

from the time series sets D, E, F and G: the site “Obidos” could be removed from sets E and G without affecting the first PC. However, the first PCs derived from sets G (covering the longer period) and C (including more sites) are not well correlated to each other. Therefore, the first PC derived from the four sites in data set G do not represent the whole Amazon River basin but only the sub-basins to the south.

The good correlations among first PCs are not seen for the second and third PCs and hence they have to be analysed separately. For example, the correlation between the second PC of time series set A and NINO 3.4 represents the influence of the Pacific Ocean SST on the second PC but only in the period 1979–1997. Likewise, the same correlation using time series set C would extend that analysis for the period 1974–2007, but only for the sites in set C whose second PC does not represent well the behavior of the whole set of 13 sites.

The coefficients of correlation between each PC and the SST indexes are shown in Table 2. Considering time series set C, which represents the first PC of the whole 13 sites well, the greatest correlations occur between the first PC and AMM (0.41) and between the second PC and NINO 3.4 (0.28), as illustrated in Figs 2 and 3. Also, the first PC explains 40% of the variance compared to 27% explained by the second PC. Therefore, the AMM, an indicator of ITCZ displacement, has greater influence on the annual variability compared to NINO 3.4 in the period from 1974 to 2007 (time series set C).

Table 2 Correlations with NINO 3.4 and AMM indexes.

Time series set	Period	Correlation with NINO 3.4:			Correlation with AMM:		
		1st PC	2nd PC	3rd PC	1st PC	2nd PC	3rd PC
A	1979–1997	–0.38	–0.21	0.25	0.50	–0.45	–0.21
B	1978–2007	–0.26	–0.42	0.03	0.34	0.10	–0.26
C	1974–2007	–0.07	0.28	0.08	0.41	–0.30	–0.10
D	1971–1997	0.20	–0.10	0.08	–0.51	–0.06	–0.19
E	1968–2006	0.25	0.03	–0.06	–0.47	0.07	–0.17
F	1932–1997	–0.17	–0.02	0.15	0.01	–0.26	–0.60
G	1932–2007	–0.22	0.03	–0.02	0.05	–0.33	0.40

The time series set E covers a longer period and excludes several sites compared to the time series set C. Still, the first PC is better correlated to the AMM index (–0.47) although it is also correlated to NINO 3.4 (0.25). However, the second and third PCs have low correlations with the SST indexes. When only the sites that drain the southern region of the Amazon River basin are considered (time series sets F and G), the first PC is better correlated to NINO 3.4 (–0.22) and the second and third PCs are more correlated to AMM (–0.33 and 0.40). Hence, when all 13 sites are considered (data set C), the AMM index drives the first PC and both the NINO 3.4 and AMM indexes drive the second PC; however, when only the sites to the south are considered (data set G) the influence of NINO 3.4 becomes stronger in the first PC, leaving the now less important influence of the AMM index to the second and third PCs.

CONCLUSIONS

The annual variability of streamflow time series in Amazonian rivers was studied by extracting the PCs from different sets of time series and correlating them with SST indexes related to both the Atlantic and Pacific Oceans. In some cases, a fewer number of time series covering longer periods could be used to derive PCs that were similar to those obtained with a greater number of time series. However, the longer time series covering the period from 1932 to 2007 did not represent the hydrological behavior in the entire basin and thus their PCs can only be used to conduct analyses in their sub-basins.

The comparison between PCs of streamflow time series and climatic indexes showed that the ITCZ displacements have greater influence on annual variability compared to the NINO 3.4 index.

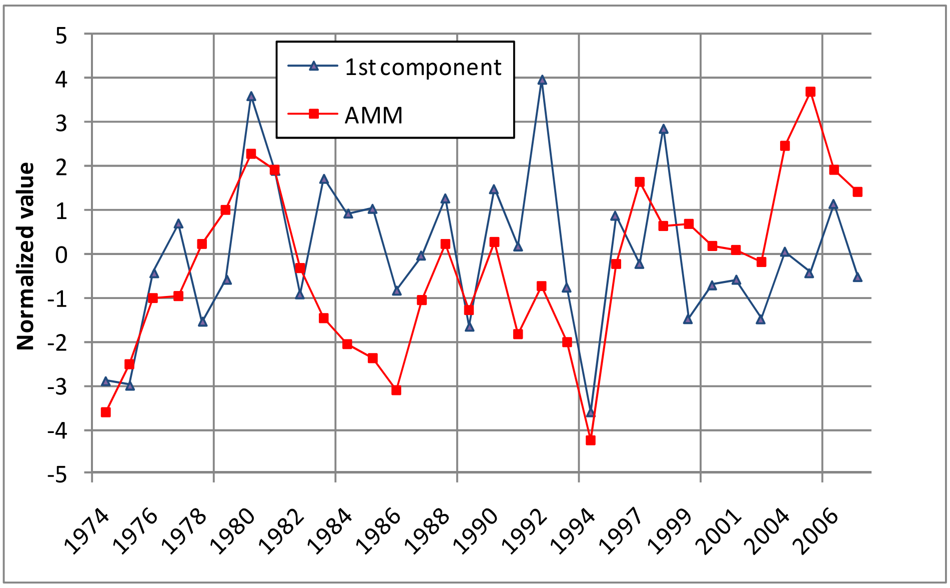

Fig. 2 First principal component and AMM index for the time series set C.

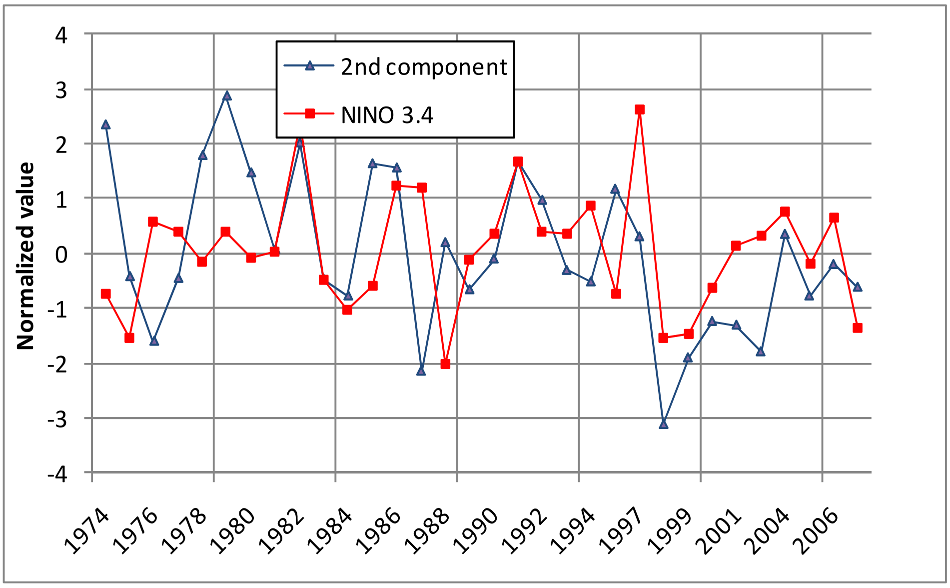

Fig. 3 Second principal component and NINO 3.4 for the time series set C.

However, when the sites draining the southern region of the Amazon basin are considered alone, the influence of NINO 3.4 becomes greater and the effect of ITCZ displacements is evident only in the second PCs. These results suggest that the annual variability in southern sub-basins is more influenced by the effects of suppressed convection triggered by El Niño events than by ITCZ displacements whose influence is concentrated in the central and northern sub-basins and eventually reaches the southern sub-basins.

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